Development of an Ultra-wide band Receiver for the North America Array

Jose E. Velazco, Melissa Soriano, Dan Hoppe, Damon Russell,
Larry D'Addario, Ezra Long, Jim Bowen, Lorene Samoska, Joe Lazio
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-4605
Jose.E.Velazco@jpl.nasa.gov

***Abstract*— The North America Array (NAA), also known as the next-generation Very Large Array (ngVLA), is a concept for a radio astronomical interferometric array operating in the frequency range 1.2 GHz to 116 GHz and designed to provide substantial improvements in sensitivity, angular resolution, and frequency coverage while reducing operational costs compared to the current Jansky Very Large Array (JVLA). At JPL, we are designing a single receiver package designed to operate across the 8 to 48 GHz frequency range, in contrast to the current JVLA, which covers this frequency range with five receiver packages. Reducing the number of receiving systems required to cover the full frequency range would reduce operating costs. We are developing a prototype integrated feed-receiver package with a system noise temperature that meets the requirements of the ngVLA/NAA primary science programs, with a design that meets the requirement of low long-term operational costs. The receiver package being developed at JPL consists of a feed horn, low-noise amplifier (LNA), and down-converters to analog intermediate frequencies. We report on the status of this receiver package development.**

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1. INTRODUCTION

The North America Array (NAA), also known as the next generation Very Large Array (ngVLA), is a concept for a new Fourier synthesis telescope (interferometric array) that will provide a large increase in sensitivity and angular resolution over the best existing telescopes (JVLA and ALMA) in the frequency range 1.2 to 116 GHz. It will also be competitive with other planned instruments (SKA1) at overlapping frequencies, but it aims to far exceed the capabilities of all other instruments above about 15 GHz. A preliminary design for the NAA/ngVLA system is currently under development, led by the National Radio Astronomy Observatory (NRAO). The concept includes about 150 to 350 reflector antennas (depending on the antenna size, which is not yet chosen) and baselines up to about 300 km with a dense core on few-km scales for high surface brightness imaging, centered at the current JVLA site in New Mexico [1].

JPL is in a unique position both to contribute to the NAA and to benefit from it. With its frequency coverage, the NAA would cover all of the deep space communication frequency allocations and all of the planetary radar frequency allocations. Figure 1 shows a preliminary estimate of effective collecting area as a function of frequency for various telescopes, including the proposed NAA/ngVLA.

The NAA could be used by JPL/NASA during key critical spacecraft events such as entry, descent, and landing or orbit insertions for missions at the outer planets or their icy moons. Historically, radio astronomy antennas have been used in the past to support such events. For example, the Very Large Array was used in conjunction with the DSN Goldstone 70-m and 34-m antennas during the Voyager Neptune encounter [2]. The Green Bank observatory was used to receive direct to earth transmissions from The Mars Phoenix Lander during its entry, descent, and landing [3].

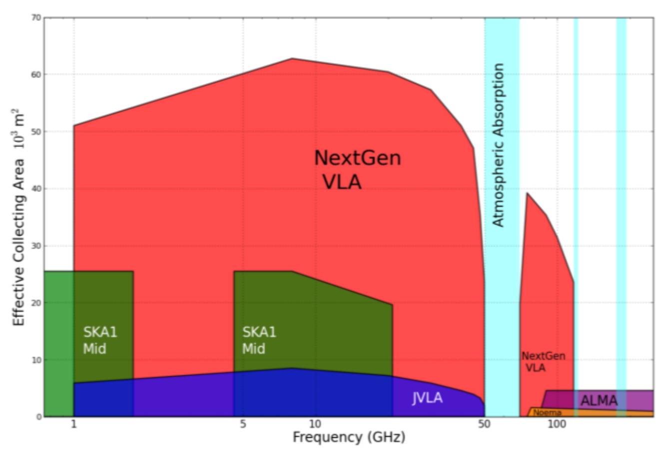


Figure 1. Preliminary estimate of effective collective area as a function of frequency for various telescopes (courtesy NRAO).

This effort focuses on the development of a prototype ultra-wideband feed-receiver package for the NAA. Much like the case for the DSN, operational costs are increasingly recognized as a factor in determining the viability for current and future radio telescopes. For the NAA to achieve the required sensitivity, the feed-receiver systems will have to be cryogenically cooled, but in order to minimize operational costs associated with the cryogenics, the number of such feed-receiver systems should be minimized. Similarly, integrated and easily serviceable feed-receiver systems are expected to reduce maintenance costs and downtime. These considerations lead us to development of an integrated, cryogenically-cooled feed-receiver package with a continuous instantaneous frequency coverage of 8-48 GHz and a system noise temperature that meets the requirements of the priority science programs of the NAA, 34 K at 10 GHz and 45 K at 30 GHz [1]. The receiver should be low cost, easy to manufacture and easy to service. In collaboration with other groups developing prototype systems for the NAA, we seek to demonstrate that key components are sufficiently mature in time for the project to be included in the 2020 Astronomy Decadal Survey.

The DSN and current radio telescope receiving systems define the state-of-the-art in receivers. DSN receivers have extremely low system temperatures, typically 25 K or better, but in fairly narrow bands (mostly at S-, X-, and Ka bands) with typical bandwidths no larger than 10% [4]. The JVLA, operated by the NRAO, currently utilizes five different receiving systems for the 8–49 GHz frequency range. The JVLA receiver frequency bands and their corresponding noise temperatures, T_{RX}, are shown in Table 1.

Table 1- T(Rx) vs Frequency for JVLA Receiver Bands

Receiver Band	X	Ku	K	Ka	Q
Frequency Range (GHz)	8-12	12-18	18-26.5	26-40	40-50
T_{RX} (K)	20	25	34	40	48

2. DESCRIPTION

The ultra-wide band receiver package under development will have direct application in the eventual implementation of the North America Array. The receiver we are designing will allow us to assess whether wideband operation in the 8-49 GHz can be achieved with a single receiver while preserving the desired receiver gain and noise temperature performance. In addition, the planned construction and testing of our receiver will provide valuable information about receiver cost and power consumption as well as operational costs. All this information will have direct impact in conceptualizing the North America Array.

The ultra-wide band receiver package, shown schematically in Fig. 2, includes a feed, low-noise amplifiers and a down-conversion stage (the feed and LNA are cryo-cooled). Responding to the combination of scientific and operational considerations, our design goals for the receiver system are:

1. Continuous frequency coverage of 8–48 GHz;

2. Down-conversion stage with multiple bands providing an intermediate frequency whose value is dependent on the number of bands selected;

3. System noise temperature of 34 K at 10 GHz and 45 K at 30 GHz as required by the ngVLA/NAA primary science programs [1];

4. 30 dB gain across each of intermediate bands.

The resulting integrated, cryogenically-cooled feed-receiver package will have a sensitivity performance comparable to current narrower band systems on radio telescopes and the DSN but with a design that responds to the requirements of lower long-term operational costs.

In this paper we present initial preliminary design results of the ultra-wide band receiver package. In Section 3, we present simulation studies of the feed horn including the insertion of dielectric components for improved illumination efficiencies across the band of interest. In Section 4, we present test and simulation results relevant to the design of the wideband monolithic microwave integrated circuit (MMIC), low-noise amplifiers (LNAs). In Section 5, we provide an initial analysis of noise temperature performance of the entire ultra-wide band receiver package. Future work is described in Section 6.

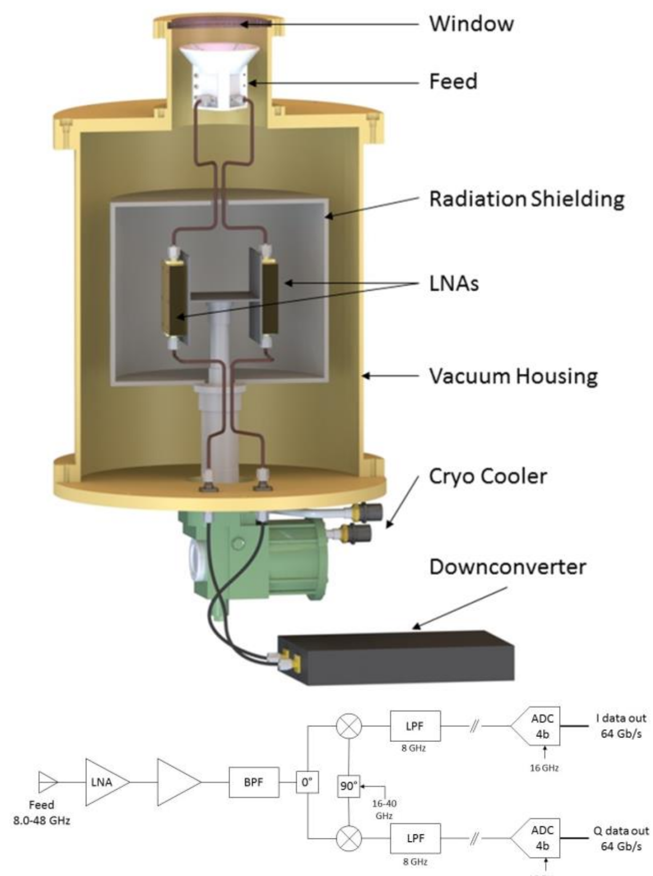


Figure 2. Initial conceptual receiver design

3. FEED DESIGN

The ultra-wide band receiver package includes a single feed, capable of operating in the 8-48 GHz frequency range (6:1 frequency ratio). The wideband feed that we are considering for this project is a scaled version of the quad-ridge flared horn antenna model QRFH-HA-6-FL developed by Sander Weinreb's group [6]. The QRFH-HA-6-FL horn is designed to efficiently illuminate microwave reflector antennas over a frequency range of FL to 6FL GHz, where FL is the lowest frequency of operation. The feed is dual-linear polarized, designed for a given half-angle, and is constructed entirely of aluminum except for the coaxial line center conductor and SMA connectors which are gold-plated steel. The feed provides two SMA outputs, one for each linear polarization, which will be used to connect to the LNA section. A version of the QRFG-HA-6-FL feed exists that operates in the range of 3 GHz to 18 GHz. We are actively collaborating with Sandy Weinreb's group on the development of a scaled up version of the QRFH-HA-6-FL for operation in the 8-48 GHz range. As part of this design work, the original feed dimensions have been scaled to operate in the 8–48 GHz frequency range. In addition, we will upgrade the feed design so that the new design will use 2.4 mm connectors that are suitable for operation up to 50 GHz.

One of the challenges in developing the feed design is that the feed must be matched to the antenna for maximum efficiency. The NAA system design, including the antenna type, is still in development. There are various pros and cons between the two primary options, offset-Gregorian and symmetric Cassegrain antennas, including efficiency, space for the receivers, performance, access for maintenance, and cost. In order to proceed with the feed design, we have currently assumed that the NAA system will use an offset Gregorian antenna, which is currently the favored option. For our feed design and associated simulations, we have assumed a version of the MeerKAT antenna scaled to 18 m diameter, with an illumination angle of 50◦.

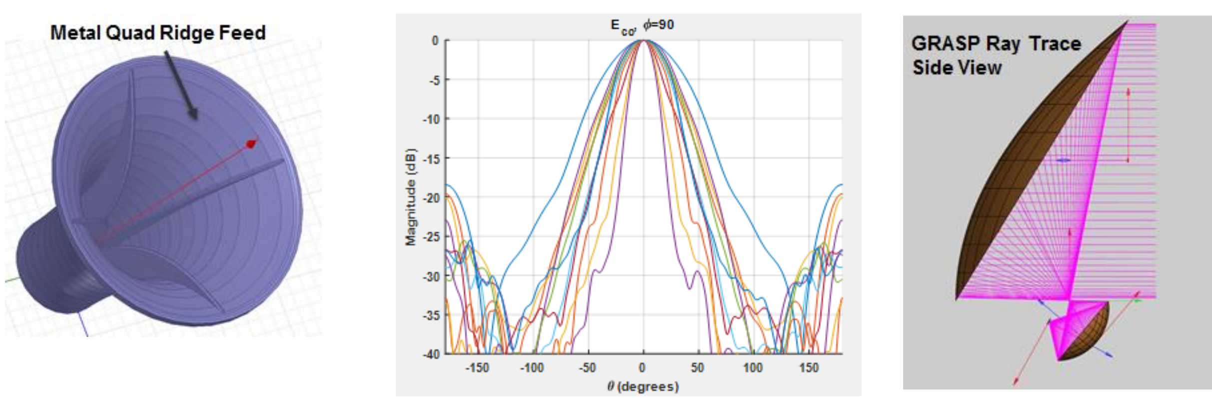
Feed requirements are shown in Table 2.

Table 2- NAA Receiver Feed Requirements

Parameter	Requirement
Return Loss	≥ 20 dB
Cross-polarization	≥ 20 dB
Focal Ratio	0.55
Efficiency	55%

Currently the MATLAB code for generating the Python scripts for HFSS is complete and the Meerkat GRASP model is also complete. MATLAB scripts are used to format the HFSS feed patterns and process the GRASP output. The software optimization loop is closed manually, using human intelligence to choose the next parameter set. We may also employ some automatic parameter sweeping to arrive at an optimum feed design. Figure 3a shows a drawing of the 8-48 GHz quad ridge feed that we are currently studying. Figures 3b and 3c show performance plots obtained for this feed with our suite of simulations codes. This version of the feed worked properly at lower frequencies while its performance degraded slightly at the higher frequency band.

We are exploring the addition of a simple tapered dielectric rod in the middle of the feed to improve performance at higher frequencies. A broadband dielectrically loaded quad-ridged feed horn was developed by the Commonwealth Scientific and Industrial Research Organisation's (CSIRO) Australian Telescope National Facility that achieved a near constant beam width over a 6:1 bandwidth from 0.7 to 4.2 GHz [7]. Our dielectric rod is simpler in design and therefore easier to manufacture. The center radius of the rod roughly determines the coupling from the horn to the rod and the length of the rod determines pattern beam width.



(a) (b) (c)

Figure 3. (a) Drawing of the 8-48 GHz feed antenna and (b),(c) performance of this antenna obtained with our suite of codes.

4. LOW-NOISE AMPLIFIER DESIGN

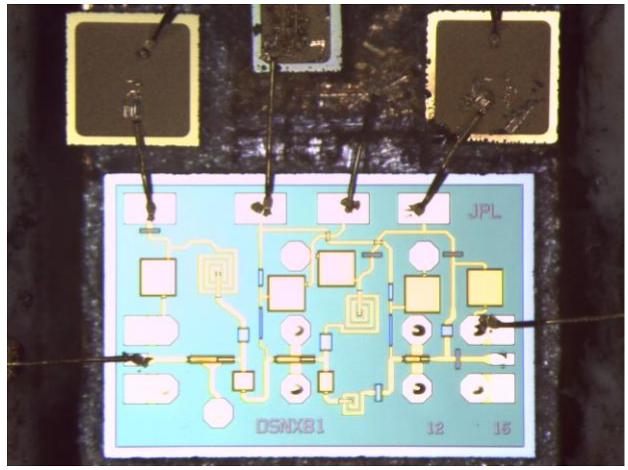
We are developing custom Monolithic Microwave Integrated Circuits (MMICs) for the NAA receiver package. We are having these MMICs fabricated at foundries, installing them in connectorized packages, and testing the packaged amplifiers. We are currently pursuing two different options: 70 nm Gallium-Arsenide (GaAs), metamorphic High-Electron-Mobility-Transistor (mHEMT) MMIC LNAs fabricated at the OMMIC foundry, and 35 nm Indium-Phosphide (InP) HEMT MMIC LNAs fabricated at the Northrop Grumman Corporation (NGC) foundry. We are testing these LNAs for broadband performance at the desired 8-48 GHz frequencies in our laboratories at Caltech and JPL. LNA requirements are shown in Table 3 below.

Table 3- NAA Receiver LNA Requirements

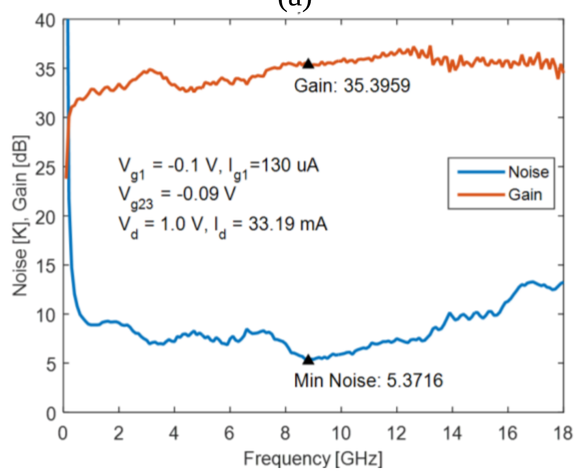
Parameter		Requirement
Noise Temperature	8-40 GHz 40-48 GHz	≤ 12 K ≤ 20 K
Gain		≥ 30 dB
Gain Flatness		≤ 6 dB
Input Match	8-15 GHz 15-48 GHz	≤ -5 dB ≤ -10 dB
Output Match		≤ -10 dB

Relevant results from a previous 70 nm GaAs mHEMT LNA wafer run are shown in Figure 4. This design was optimized for 8.4 GHz. Figure 4a shows a picture of the LNA. In Fig. 4b one can observe the broadband operation of these devices along the 1-18 GHz range. Note that at 8 GHz (DSN spacecraft communications band) we obtained a noise temperature of 5.4 K and a 35 dB gain. Several LNA wafer runs dedicated to this project are planned. The first 70 nm GaAs mHEMT design was scaled up from the 1-18 GHz design up to the 8-48 GHz range and was completed in the summer of 2016. Figure 5 shows an image of the as-designed 8-48 GHz, 1.5 mm x 1 mm, MMIC LNA. Also shown next to the MMIC is the corresponding LNA housing that we just completed.

Simulation results for this design are shown in Figure 6. ~10 K noise temperature performance is obtained in the 8-30 GHz frequency range. The run was submitted to OMMIC for fabrication and we expect to receive the LNA wafers from this first design in early January. Once we receive these devices we will perform complete testing in our laboratories to assess their noise temperature and gain performance across the entire 8-48 GHz band.



(a)



(b)

Figure 4. (a) Photomicrograph of a JPL MMIC for 1-18 GHz, manufactured in the OMMIC 70-nm GaAs mHEMT process. (b) Measured noise temperature and gain vs. frequency for an LNA that uses this MMIC.

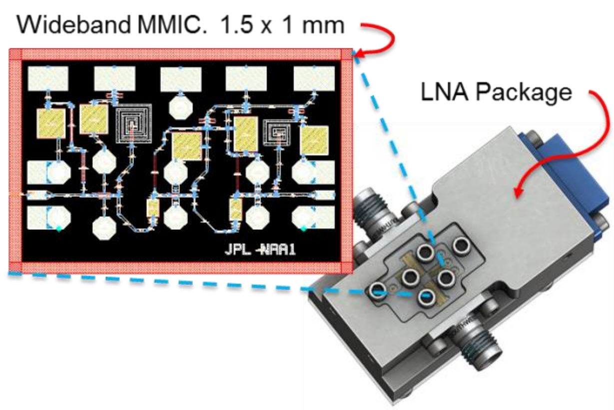


Figure 5. Layout of JPL MMIC design for 8-48 GHz and CAD rendering of a connectorized housing for it.

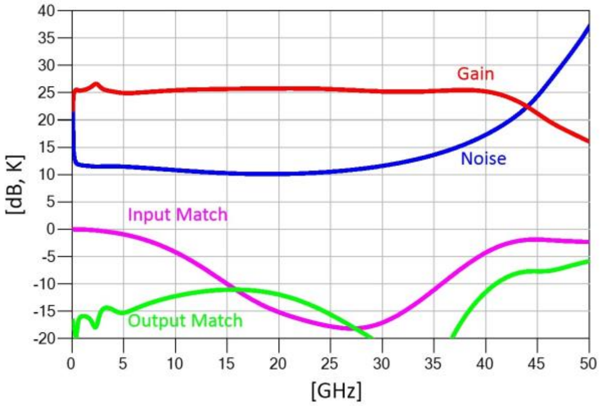


Figure 6. Simulated gain, noise, and matching performance of the 8-48 GHz MMIC LNA design shown in Figure 5, using OMMIC 70 nm GaAs mHEMT transistors.

We are also investigating 35 nm InP HEMT LNAs fabricated by Northrop Grumman Company (NGC). In light of recent record-performance in W-Band [8], we expect MMIC LNAs for this process to have 10-17K noise in an optimized design for 8-48 GHz. We are basing our 8-48 GHz LNA design on the work carried out by Ahmed Akgiray [9].

5. NOISE BUDGET

We have developed a preliminary noise temperature budget that includes the expected contributions of all the ultra-wide band receiver components. These components include the feed, dielectric rod, window, feed to LNA transmission line, LNA and post amplifier. This budget does not include the contribution of the downconverter components. In Table 4 we have tabulated the noise contribution of these components for four frequencies, namely, 8, 15, 32 and 48 GHz. The receiver temperature, which includes all the components' contributions, is referred to as Trx. Note that at the lowest frequency Trx = 19 K whereas at the top of the frequency range, Trx = 34 K. Noteworthy is the fact the main contributor to system noise is the LNA.

Table 4- Receiver System Noise Budget

Noise (K)	**@ 8 GHz**	**@ 15 GHz**	**@ 32 GHz**	**@ 48 GHz**
Feed	1	2	3	3
Dielectric Rod	1	1	1	1
Window	3	3	3	3
Feed to LNA	1	2	3	3
LNA	12	12	12	20
Post Amplifier	1	2	3	4
T_{rx} (K)	**19**	**21**	**25**	**34**

6. Future Work

This work is part of a JPL Research and Technology Initiative. We are currently in the second year of this three-year initiative. We will soon receive the first 70 nm GaAs mHEMT LNA wafer run back from OMMIC and we will then test and evaluate performance of this first design. Based on these test results, we will develop a second revised 70 nm GaAs mHEMT design and send it to OMMIC for fabrication, scheduled from April of 2017. We also plan to develop a 35 nm InP HEMT design in parallel. We will complete the optimization of the QRFH design with a dielectric rod and fabricate this feed. We plan to evaluate options for the receiver's cryogenics and finalize the cryogenic system and receiver package design. We will also work on the downconverter design. We expect to have a prototype receiver complete in September 2017. It will then be tested on an existing antenna comparable to the NAA antenna.

7. Acknowledgements

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

8. Summary

We have presented preliminary results of an 8-48 GHz ultra-wide band receiver development for the future North America Array. Results were presented for the feed design that was carried out via iterative optimization with our suite of codes. We are currently studying the insertion of a dielectric rod in the middle of the feed to improve feed performance at the higher frequency. Results of the feed optimization including the dielectric rod will be reported in future publications. We also reported on the 70 nm GaAs mHEMT LNA designs we are pursuing from the foundry OMMIC. Our initial receiver noise temperature calculations indicate that our receiver design can meet the system noise temperature required by the ngVLA/NAA primary science programs.

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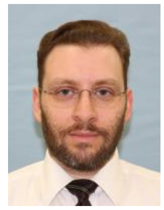
BIOGRAPHIES

Dr. Jose Velazco *is the principal investigator for the Ultra-wide band Receiver for the North America Array program and has over 20 years of experience in carrying out R&D projects. Dr. Velazco has extensive experience in implementing wideband receivers for electronic surveillance applications including wide-open and superheterodyne receivers. Dr. Velazco is the technical supervisor of the Applied Electromagnetics Group at the Jet Propulsion Laboratory, which develops state-of-the-art high sensitivity cryogenic receivers for NASA's Deep Space Network.*

Melissa Soriano *is the North America Array Initiative Lead at JPL. Melissa graduated with a B.S. from Caltech, double major in Electrical and Computer Engineering and Business Economics and Management. She also received a Masters in computer science from George Mason University. She has developed real-time software for receivers and antenna array systems used in the Deep Space Network. She was responsible for Direct to Earth communications with Mars Science Laboratory during entry, descent, and landing, and communications with Juno during Jupiter orbit insertion.*

Daniel J. Hoppe *received the B.S. and M.S. degrees in electrical engineering from the University of Wisconsin Madison in 1982 and 1983, and the Ph.D. degree, also in electrical engineering, from the University of California Los Angeles in 1994. He is currently a principal engineer at the Jet Propulsion Laboratory. His work there involves electromagnetic analysis and design of microwave and optical devices for both ground-based and space-based applications.*

Dr. Larry D'Addario *is a senior electronics engineer at Jet Propulsion Laboratory, where he works on spacecraft communication and inter-planetary radar for NASA, and also studies signal processing for large radio telescopes. He is also a Visitor in Radio Astronomy at Caltech, where he works on development of new radio telescopes. He received his PhD from Stanford University. Prior to joining JPL, he worked at the NRAO for 30 years, where he helped design the VLA, VLBA, GBT, and ALMA, and built a tracking station for space VLBI.*



Ezra Long *is a microwave engineer at the Jet Propulsion Laboratory, California Institute of Technology. He received a BA in mathematics and an MSEE from California State University Northridge. His career at JPL has focused on cryogenic low-noise receivers for the Deep Space Network. In addition he has extensive experience with antenna and microwave metrology.*

James Bowen *has had extensive experience in development of cryogenic LNAs since starting at the Jet Propulsion Laboratory in 1984. He has worked on development of Low Noise HEMT amplifiers for the Deep Space Network and Radio Science applications. He has also developed and delivered several cryogenic front ends and feed assemblies including control and instrumentation electronics to the DSN and other observatories.*

Lorene Samoska *(M'95–SM'04) received the B.S. degree in Engineering Physics from the University of Illinois in 1989, and the Ph.D. degree in Materials Engineering from the University of California, Santa Barbara, in 1995. She worked as a post-doctoral researcher at UC Santa Barbara in the design and fabrication of state-of-the-art InP HBT microwave digital circuits. She joined the Jet Propulsion Laboratory in 1998, where she is currently a Principal Engineer involved in the design and testing of 30-600 GHz HEMT MMIC low noise amplifiers and receivers, and power amplifiers for local oscillator sources and transmitters in future space missions.*

Dr. Joseph Lazio *is Chief Scientist of the Interplanetary Network Directorate at the Jet Propulsion Laboratory, California Institute of Technology. The Interplanetary Network Directorate manages the Deep Space Network for NASA's Spacecraft Communications and Navigation (SCaN) Division. He received his Ph.D. from Cornell University, was a U.S. National Research Council Research Associate at the U.S. Naval Research Laboratory, and was a Radio Astronomer on the staff of the U.S. NRL, before joining JPL. He was the Deputy Principal Investigator for the proposed Dark Ages Radio Explorer (DARE). He has served as Project Scientist for the Square Kilometre Array (SKA); the Deputy Director of the Lunar University Network for Astrophysics Research (LUNAR); and as Project Scientist for the U.S. Virtual Astronomical Observatory. He also observes routinely with the world's premier ground-based radio telescopes, including the Expanded Very Large Array, the Very Long Baseline Array, the Green Bank Telescope, the Giant Metrewave Radio Telescope, and the Australia Telescope Compact Array.*